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An Autonomous Investigation of Kuroshio and Mesoscale Impacts on Upper Ocean Response to Typhoon Forcing

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Upper ocean response to atmospheric forcing.
- Submesoscale dynamics of the mixed and transition layer.

This program also follows the team's long-term focus on developing new approaches for exploiting autonomous technologies for conducting process-level measurements.

OBJECTIVES

- Characterize the upper ocean response to typhoon forcing, in particular the temporal and spatial evolution of the cold wake generated by a typhoon.
- Demonstrate the utility of a new glider-borne microstructure sensor package for collecting high-quality turbulence measurements over the course of long-duration (weeks to months) deployments.

APPROACH

The Impact of Typhoons on the Ocean in the Pacific (ITOP) program brought together an international team of oceanographers and atmospheric scientists to conduct a highly collaborative investigation of the oceanic response to typhoon forcing. Novel aspects of this program included the availability of C130 aircraft capable of air-dropping autonomous assets directly in front of propagating typhoons and extended access to a global-class research vessel, R/V Roger Revelle, stationed in Kaoshiung and capable of carrying autonomous assets and rapid survey capability into the typhoon's cold wake, shortly after the storm's passage. This permitted direct measurement of both the immediate response to the typhoon's passage and the longer timescale evolution of the resulting cold wake. This project focused on understanding cold wake evolution using a fleet of ten long-endurance autonomous Seagliders (three of which were equipped with temperature microstructure sensors) and ship-based surveys employing a rapid-profiling underway CTD.

The success of the ITOP program depended on choosing and carefully targeting an appropriate storm. During the height of the 2010 typhoon season (August-October), Western Pacific convective systems were continuously monitored using remote sensing, reanalysis models, and targeted aircraft

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measurements. Although aircraft-supported assets could deploy into multiple typhoons, the ship-based cold wake study possessed only enough ship days to target a single event. The cold wake team chose Typhoon Fanapi, a category-3 typhoon that formed on 14 September, made landfall in Taiwan on 19 Sept., and dissipated on 22 Sept. over mainland China. As typhoon Fanapi developed, the storm was monitored and its wind field measured using a large number of dropsoundes. Floats and drifters dropped in front of the storm measured the oceanic response (D'Asaro et al. 2012). A ship-based effort (one component of the overarching ITOP program) using R/V Roger Revelle targeted Fanapi's cold wake from 17 September to 11 October 2010. The general objective of the cruise was to understand how the ocean responds and recovers after the passage of a strong typhoon, focusing in particular on the cold wake formed along the typhoon track.

R/V Revelle arrived at the cold wake less than four days after the storm, deploying gliders and conducting ship-based sampling at two primary sites (Figure 1). The cold wake at Site A formed on 18 Sept. under an intense (>50 m/s winds), but fast-moving storm. The narrow, well-defined wake was rapidly capped by strong net surface heat fluxes associated with clear skies following Fanapi's passage. The wake was also highly strained, presumably by the mesoscale circulation. After sampling Site A for roughly one week, Revelle shifted focus to study the south-west edge of a large, persistent cold pool formed earlier, when the storm was intensifying and moving slowly (Site B).

A total of ten glider missions were conducted during ITOP, employing eight of the eleven Seagliders prepared and shipped for the project. Eight gliders surveyed the regions around Site A, sampling both within and outside of the wake. Six of these continued surveying Site A while Revelle switched focus to Site B, with two gliders recovered and redeployed at Site B. Two gliders were recovered at the end of the cold wake cruise, with six continuing to sample until 10 Oct., when they were recovered by R/V Revelle during a later ITOP cruise (Figure 1). To better resolve variability on shorter timescales (such as internal waves), ITOP gliders limited dive depths to 500 m and cycled rapidly, completing a profile every two hours.

WORK COMPLETED

Seagliders

In total, the ITOP gliders conducted ten missions in the wake of typhoon Fanapi, collecting 3100 profiles to 500 m, including 580 profiles with temperature microstructure.

Underway CTD

An Underway-CTD, manufactured by the OceanScience Group (Figure 2) was used to complete 3162 casts: 82 casts to 400-m (18 min cycles at 10 kts), 8 casts to 850 m (20 min cycles, holding station during the AXBT calibration C-130 flight) and the remaining mostly to 160 m at 10 kts (every 6 min). Instrument failures and operator errors resulted in missing data for a few profiles: 2917 uwCTD profiles were recorded (92% success rate). The uwCTD was operated almost continuously for three weeks, employing four probes with two losses.

RESULTS

Fanapi created an intense (<2°C) cold wake. Air-deployed floats and drifters (deployed by D'Asaro, Sanford, Niiler, Centurioni, etc.) captured the initial formation and evolution, and the ship and glider measurements captured the subsequent evolution over a period of several weeks. Solar radiation quickly capped the cold wake, making it difficult to detect in satellite SST image. Direct measurements

collected 4 days after the storm show a clear cooling of the upper 50 m just to the north of the typhoon track (Figure 4).

In-situ observation revealed that the cold wake persisted for several weeks, and was still present a month after the storm (Figure 4). Phenomena on several time and spatial scales govern evolution of the cold wake, including inertial motions, mesoscale eddies, propagating waves and submesoscale mixed layer eddies. The complementary combination of ship (moving fast and providing large spatial coverage) and gliders (providing persistent measurements over smaller regions) allow wake evolution to be characterized over a period of several weeks. The evolution of the temperature field in and around the cold wake is the main theme of Rosalinda Fortier's graduate work (supervised by Eric D'Asaro) – we are also providing guidance and support to her.

Internal waves

Storms are known to generate large inertial currents in the mixed layer. Convergence and divergences of these motions are also responsible for large oscillations of the base of the mixed layer, and subsequent transfer of a large fraction of the energy input by the wind to the ocean as near-inertial internal waves propagating in the interior of the water column. Near-inertial internal waves can have significant vertical shear, therefore providing an efficient mechanism for enhancing local dissipation (through internal wave breaking).

Large vertical shears are observed at the base of the cold wake (Figure 5). Time series of shear (measured by uwCTD) in the depth range corresponding to the base of the cold wake (here 24 to 26°C, roughly 60 to 80 m) shows a persistent inertial signal for the entire duration of the cruise (Figure 6). Note that the ship surveyed a large (~200 km) area during this period, obscuring details of the inertial response when considering only measurements collected from Revelle. However, the large density of gliders, floats, and drifters scattered across the track of Fanapi provides an unprecedented dataset to study the evolution of inertial waves during and after a strong storm.

Seagliders do several dives every day (10 to 12 dives per day for the rapid profiling employed during ITOP), allowing for accurate estimation of isopycnal displacements associated with internal waves. Because the ITOP cruise took place near the generation sites of large internal tides (e.g., Luzon Strait), displacement fields are a complex superposition of tidal and inertial frequencies (Figure 7). These can be separated and analyzed individually. The inertial displacements of all the gliders (Figure 8) reveal a complex wave field that evolves both in space and time. Ongoing efforts focus on synthesizing this data with that obtained from floats and drifters to obtain a complete picture.

Temperature microstructure

An important contribution of this project has been the successful integration of turbulence sensors onto the Seagliders (Figure 3). Small fluctuations in high-wavenumber temperature gradient (Figure 9) are associated with turbulence. Two redundant thermistors measure the temperature field at 100 Hz. Onboard processing computes wavenumber spectra for blocks of data of several seconds (a few meters in the vertical) and the glider transmits an integrated value in a range of wavenumbers that excludes the noise at the conclusion of each dive. This real-time data can be directly related to the rate of dissipation of thermal variance (and to rate of dissipation of kinetic energy). Data processing using the full 100 Hz data is done after recovery (Figure 10), and has been found to agree well with the real-time processing (Figure 11). Seagliders provide reliable near real-time measurement of turbulence.

Glider measurements collected during ITOP highlight the episodic and localized nature of turbulence (Figure 12). Dissipation estimates can vary by order of magnitude from profile to profile, and are

generally linked to the strain of the density field. A full analysis of the turbulence measurements collected during ITOP is underway.

RELATED PROJECTS

The ITOP measurements took place in region where with large internal tides, propagating from Luzon Strait. Knowledge of the dynamics of those waves will be an important factor for the interpretation of the various ITOP datasets. Studying the eastward propagation from Luzon Strait is also one of the objectives of the IWISE DRI. We are evaluating the existing data (drifters, floats, gliders) east of Luzon and working with modelers (Simmons, Ko) on these questions.

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PUBLICATIONS

This project has contributed to the overview paper of ITOP (D’Asaro et al., 2011). The thermal evolution of the cold wake is described in a paper currently in press (Mrvaljevic et al. 2013).

A publication about the development of the Tmicro glider is in progress, as well as another one on the inertial wave field generated by typhoon Fanapi. This latter publication will include glider and ship data, as well as drifter and float data (in collaboration with Luca Centurioni, Jan Morzel, Eric D’Asaro, Tom Sanford, and Ren-Chieh Lien).

E. D’Asaro, P. Black, L. Centurioni, R. Fortier, P. Harr, S. Jayne, I-I Lin, C. Lee, J. Morzel, L. Rainville, T. Sanford and D. Tang, 2011 Typhoons and the Ocean in the Western North Pacific, *Oceanography Magazine***, 24,** 24-31.

Mrvaljevic, R.K., P. G. Black, L.R. Centurioni, Y.-T. Chang, E.A. D’Asaro, S.R. Jayne, C.M. Lee, R.-C. Lien, I.-I. Lin, J. Morzel, P.P. Niiler, L. Rainville, and T.B. Sanford, . Observations of the cold wake of Typhoon Fanapi (2010), *2013, Geophys. Res. Lett*., **in press**.

FIGURES

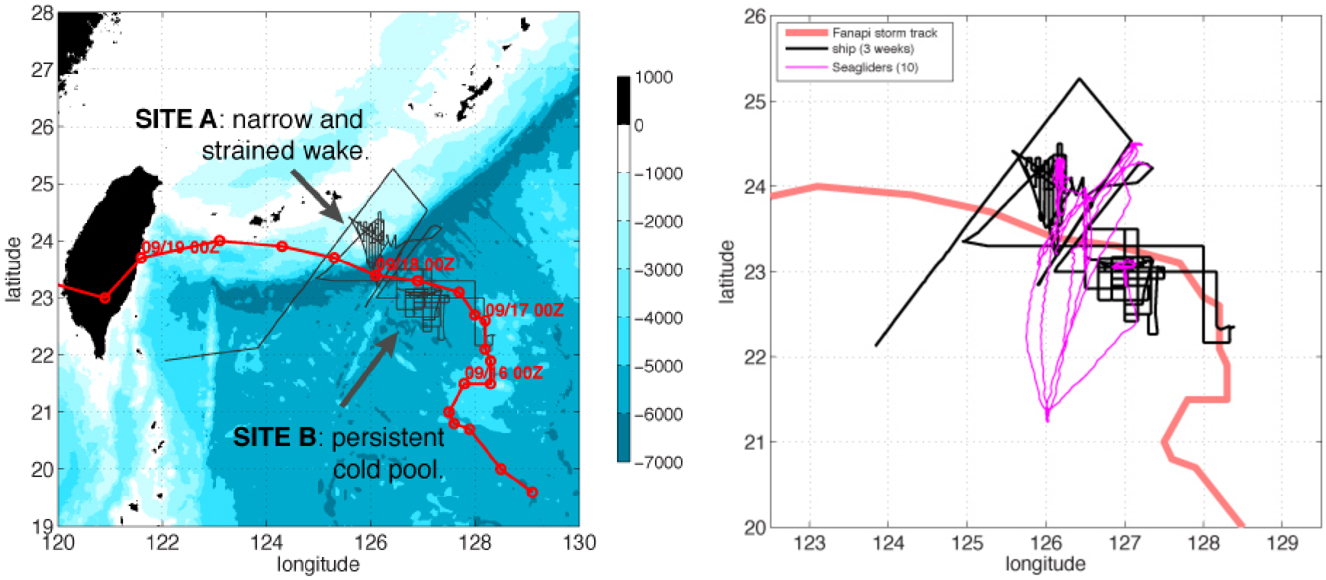

Figure 1. Left panel: Cruise track of the Revelle (black) during the Cold Wake cruise. The typhoon track is indicated in red. Ship sampling was concentrated on 2 distinct sites: Site A near 24°N 126°E, and Site B near 23°N 127°E. Right panel: Glider (magenta) and ship (black) tracks. 10 glider missions sampled the evolution cold wake, providing persistence and anchors to relate the ship measurements.

Figure 2. Underway CTD in operation during ITOP. We collected over 3000 temperature profiles of the upper 200 m during the 3-week cruise.

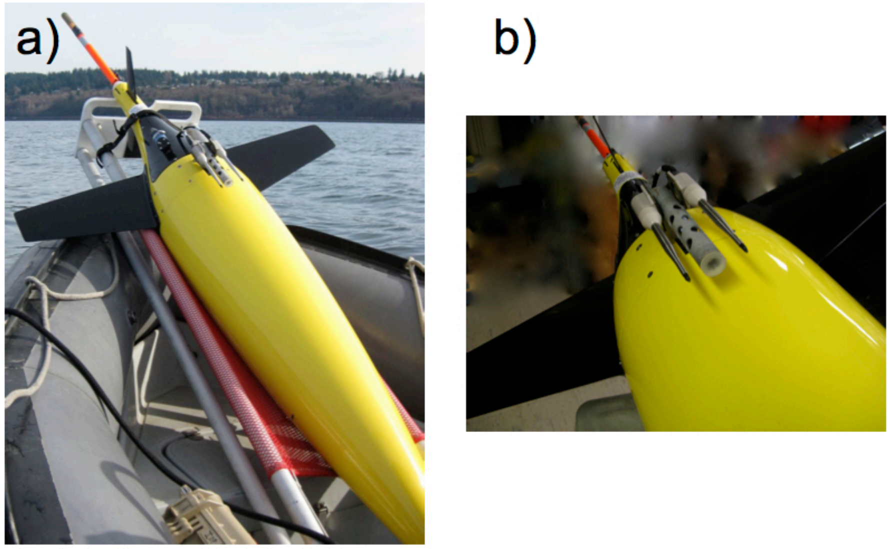

Figure 3. Seaglider equipped with micro-temperature sensors. Two small fast thermistors are mounted on either sides of the top-mounted conductivity-temperature cell, adding minimal drag and disturbance.

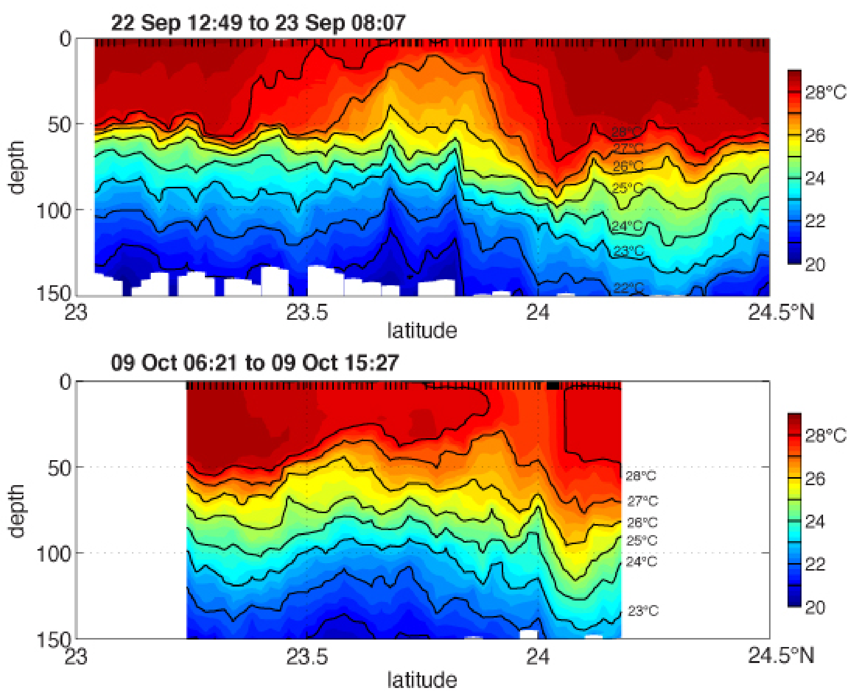

Figure 4. Temperature section across the cold wake of typhoon Fanapi 4 days (top) and 21 days (bottom) after the passage of the storm. The typhoon was centered on 23.5°N. Isotherms are contoured with an interval of 1°C. 102 and 86 profiles recorded from an underway CTD compose the stations, respectively (tick marks at the top of each panel). In the first section, note that the upper few meters of the ocean were rapidly restratified by solar heating, but the sub-surface cold wake is evident, particularly from the spreading of the 26-27 isotherms. Three weeks after the storm (bottom panel), spreading in the same temperature range is still evident.

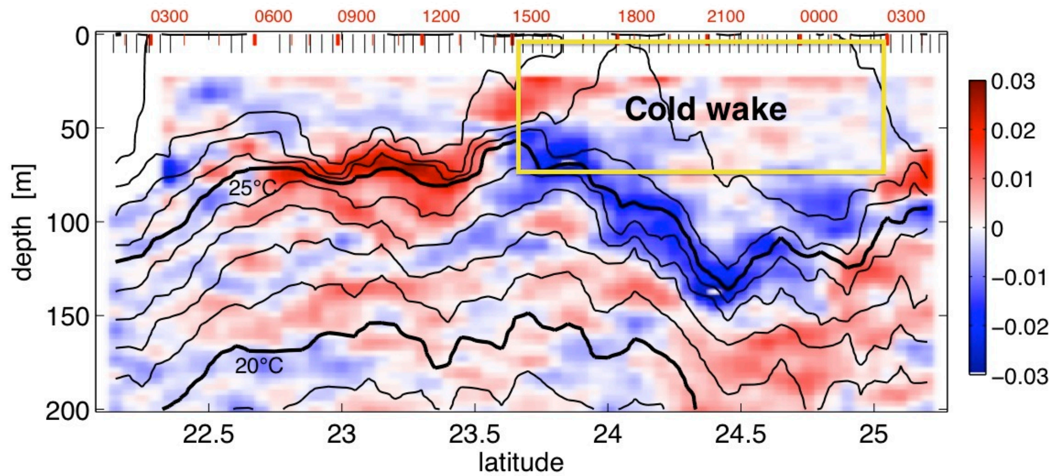

Figure 5. Vertical shear in zonal velocity along the first section across the cold wake with temperature contours (1°C intervals). Locations of the uwCTD profiles (black ticks), and time along the transect (red), are marked on top of the panel. Large shears are observed in and south of the cold wake.

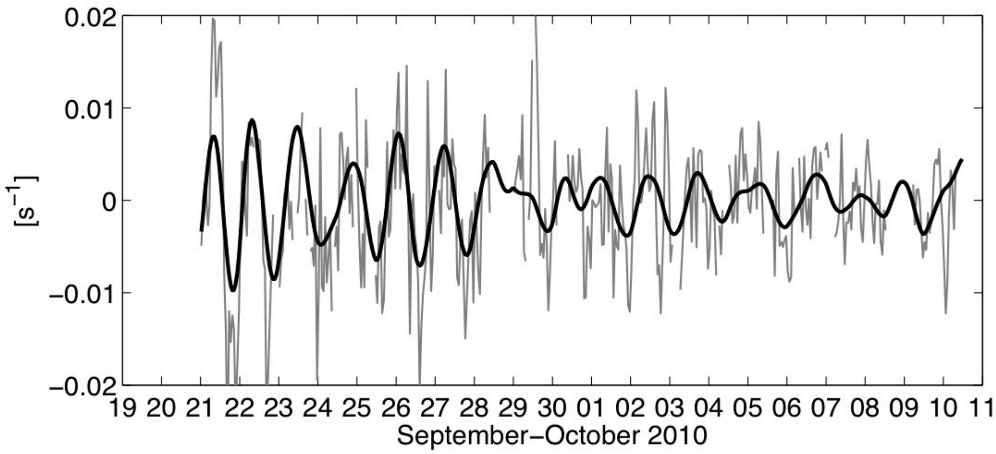

Figure 6. Zonal velocity shear of the velocity rotating clockwise in time at the inertial frequency, averaged between 24 and 26°C (i.e., the base of the cold wake). Total zonal shear in this depth range (not only inertial) is shown in gray. This is calculated by combining data from the Hydrographic Doppler Sonar System and uwCTD for the entire cold wake cruise. Although this covers a relatively large area in space, a persistent inertial and decaying signal is observed.

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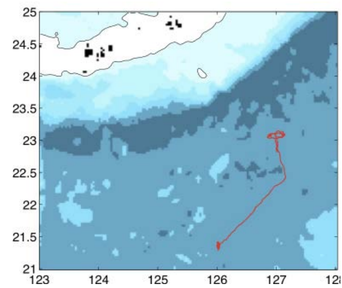

Figure 7. Temperature and isopycnal displacements estimated from a Seaglider during ITOP. The track of the glider is shown in the lower right panel. Inertial, semidiurnal, and diurnal waves are fitted to the observed displacements (lower left panel), providing an estimate of amplitude and phase of the internal tides and near-inertial waves for the entire glider deployment.

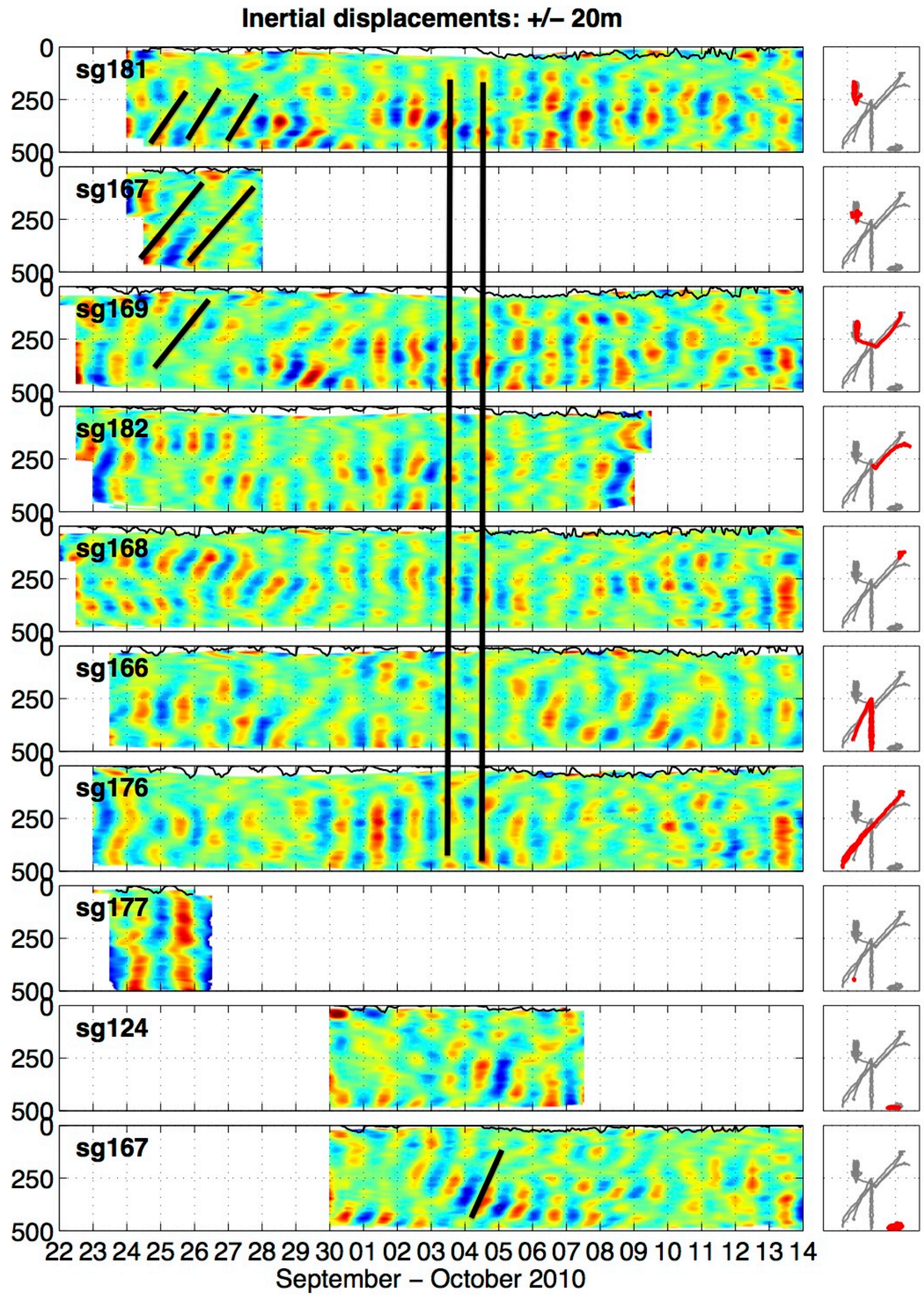

Figure 8. Isopycnal displacements associated with near-inertial waves from the 10 ITOP Seaglider deployments. The track of each glider (in red) is shown superposed to the map of all tracks on the right panels. Early in the deployments and near the cold wake, gliders measured vertically propagating inertial waves with sloped phase lines (sg 181, 167, 169 and 182). The inertial wave field becomes generally more vertically coherent – and coherent over large distances as well – as time goes by.

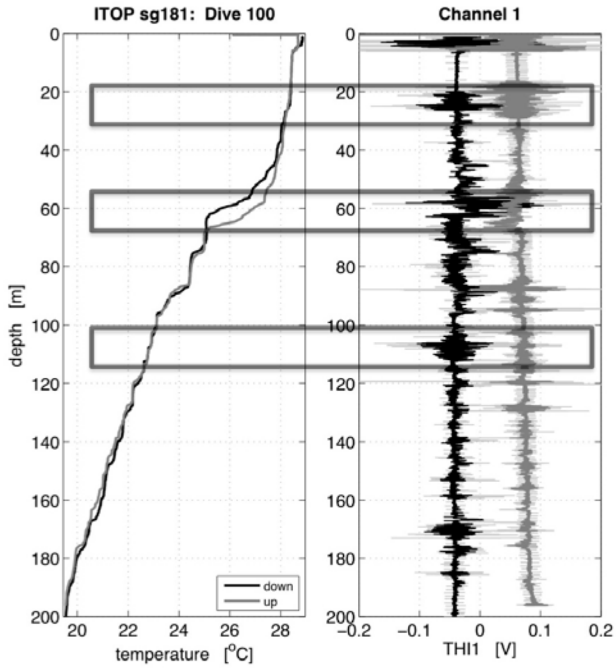

Figure 9. Typical temperature profiles collected during ITOP (down in black, up in gray), and associated temperature microstructure signal (up signal, in gray, is offset by 0.1 V). Regions of elevated signals are highlighted in the gray boxes.

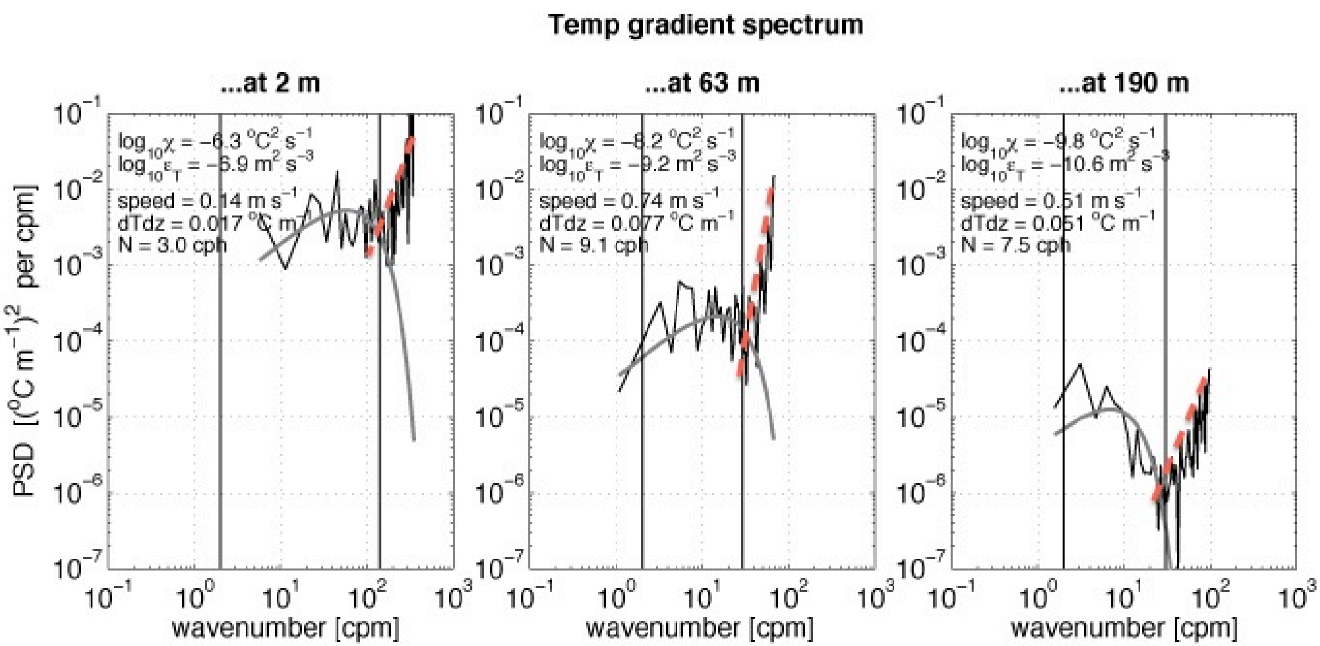

Figure 10. Examples of temperature gradient wavenumber spectra for the profiles shows in figure 10. The thin vertical lines indicate the range where the measured spectrum (black) is fitted to the Batchelor spectrum (gray). Dashed red lines indicate an estimate of the noise level at high-wavenumbers.

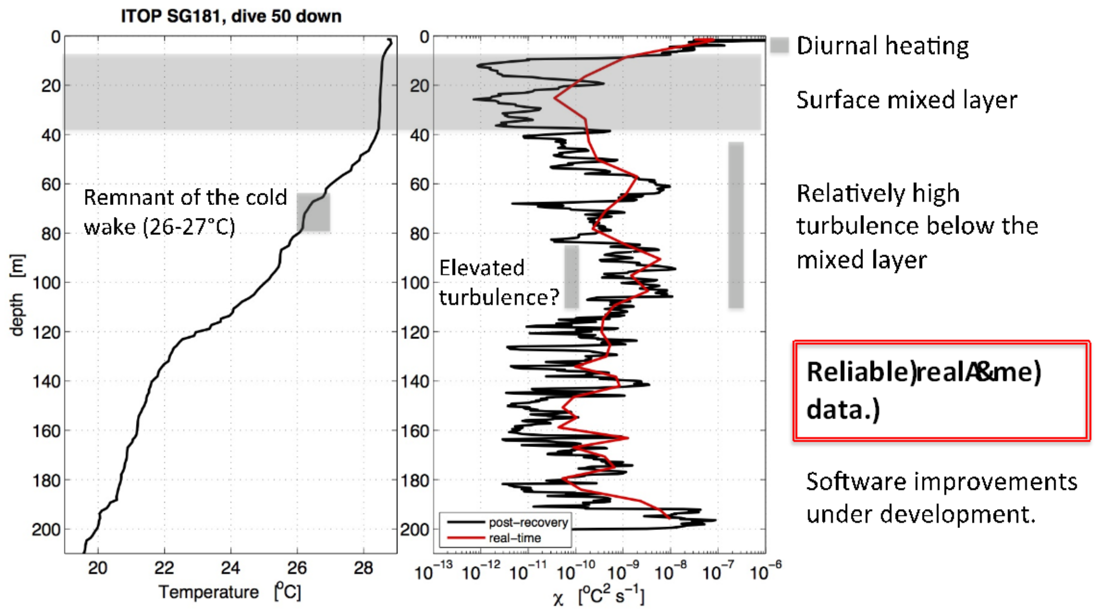

Figure 11. Example of profiles of temperature (left) and of rate of dissipation of thermal energy (χ_T, right) collected during ITOP. RHS: The red line shows the profiles obtained via onboard processing and transmitted in real-time, and the black line indicates profile obtained after recovery by processing the raw data (collected and saved at 100 Hz).

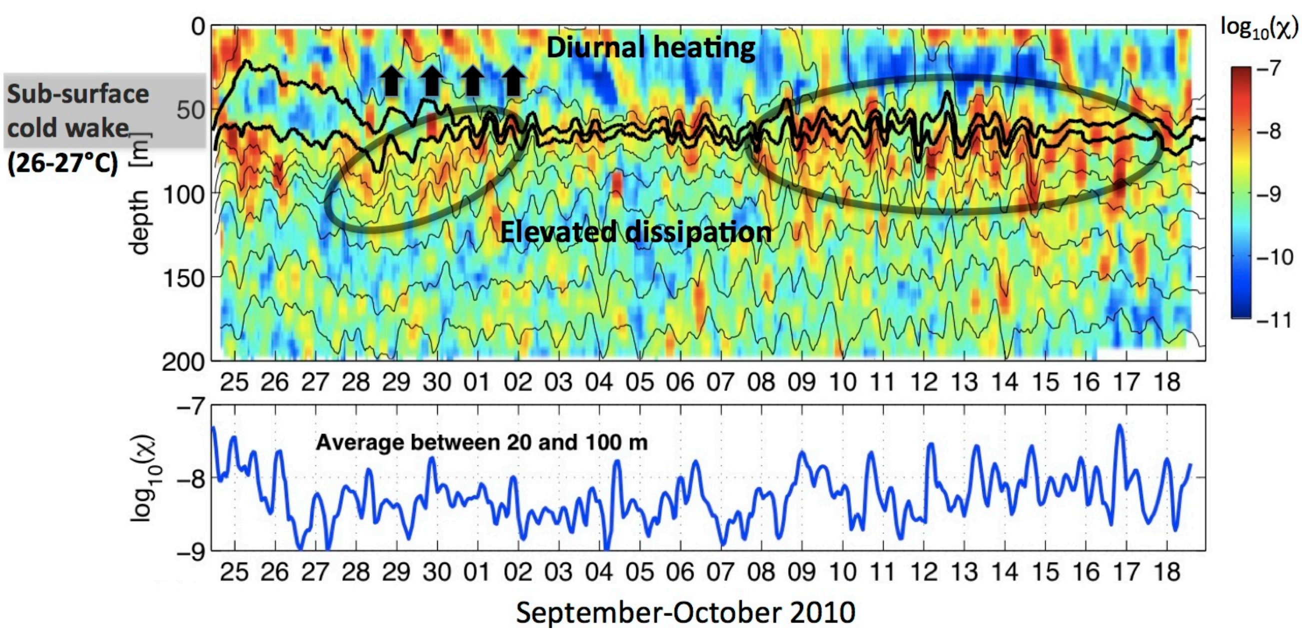

Figure 12. Timeseries of χ_T collected by a Seaglider in the wake of typhoon Fanapi. The top panel shows the rates of dissipation of thermal variance (logarithmic scale), with isotherms are contoured in black, separated by 1°C. Note the enhanced dissipation propagating downward through the mixed layer, and the elevated dissipation around the isotherms marking remnants of the sub-surface cold wake (26 and 27°C, in heavy black lines). This figure shows 269 (out of 580 total) dives of χ_T measurements.